ANALYSIS OF STIFFNESS CALCULATION METHODS FOR BIOMECHANICAL TESTING WHEN LOADING AND MEASUREMENT ARE NOT COINCIDENT SPATIALLY

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Abstract

Side impact automobile collisions are a frequent cause of serious injury. In recent years, the amount of attention being paid to these kinds of accidents has increased as evidenced by the implementation of side airbags in most commercial vehicles. Approximately one third of all occurrences of side impact automobile accidents occur in intersections when vehicles travelling at around 30 mph strike vehicles travelling around 15 mph.[1] Impacts of this variety create a loading environment with the primary force of impact at an oblique angle to the passengers. Having the capability to reduce the threat to passengers from these types of accidents requires a thorough understanding of the human body response to both oblique and lateral impacts. Currently, anthropomorphic test devices, or crash test dummies, only quantify thoracic deflection, which is the leading indicator for thoracic trauma, in the purely lateral direction. This limits the ability for the ATD to accurately depict the nature of the human thorax under any loading that is not primarily lateral. To improve on NHTSA standards of protection, a better understanding of the human response to oblique, blunt loading is necessary to improve the biofidelity of ATD's.

The motivation behind this study is to clarify differences seen in two related studies done in the Injury Biomechanics Research Lab previously. In 2006, Shaw et al observed the post-mortem human subject (PMHS) response to low energy impacts in both lateral and oblique directions.[2] Lateral impacts showed a higher stiffness than oblique impacts according to Shaw. In 2009, a study by Long used a similar protocol but impacted subjects at speeds of 4.5 and 5.5 m/s, a more injurious energy level.[3] In contrast to Shaw's study, the results of their tests indicated similar stiffness responses in both lateral and oblique impacts. To clarify the results of these two studies, their data was reanalyzed using seven different methods for calculating stiffness. The raw data was zeroed, filtered, and inertially compensated before calculating stiffness. The method with the most consistent results across all of the tests between Shaw and Long's studies, as well as studies completed since 2009, was calculating stiffness, force per unit deflection, from the time of impact to the time of maximum force. From the tests available, lateral and oblique impacts at 4.5 m/s speeds showed a similar response, 33.92 N/mm versus 36.99 N/mm, and a different response at 2.5 m/s speeds, with oblique impacts maintaining relatively the same stiffness (35.08 N/mm) while lateral stiffness increased to 65.69 N/mm. These results support the case that lateral and oblique impacts produce different biomechanical responses.

Acknowledgements

I would like to take this opportunity to thank Dr. John H. Bolte IV for giving me this chance to get invaluable research experience with himself and his team. I would also like to thank Dr. Amanda Agnew and Dr. Yun Seok Kang for answering all of my questions and giving me chances to get hands on with the research. The rest of the team at the Injury Biomechanics Research Lab at The Ohio State University, including Angela Manning, Kyle Icke, Amie Draper, Alexis Dzubak, and Laura Boucher also deserve a big thank you for all that they do. Finally, I'd like to thank Brian Suntay and all of the other employees at NHTSA VRTC that helped collect all of the data that is integral to this work.

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Chapter 1: Background

1.1 – Clinical Significance

Side impact automobile collisions are a frequent cause of serious injury. In recent years, the amount of attention being paid to these kinds of accidents has increased as evidenced by the implementation of side airbags in most commercial vehicles. Approximately one third of all occurrences of side impact automobile accidents occur in intersections when vehicles travelling at around 30 mph strike vehicles travelling around 15 mph.[1] Impacts of this variety create a loading environment with the primary force of impact at an oblique angle to the passengers. Vehicle accident records have been shown to support this claim, with a median primary direction of force (PDOF) of 60° observed in cars manufactured in 1995 or later.[2] Having the capability to reduce the threat to passengers from these types of accidents requires a thorough understanding of the human body response to both oblique and lateral impacts.

National Highway Traffic and Safety Administration (NHTSA), the governing body when it comes to automobile safety, has published standards requiring protection of the passengers involved in side-impact vehicular accidents. Evaluating compliance with these standards relies heavily on anthropomorphic test devices (ATD's), also known as crash test dummies. ATD’s are designed to be biofidelic, meaning to correlate well with the response seen in the human body under the same conditions. The standard indicator of thoracic trauma in ATD’s is rib deflection. Currently, ATD’s only quantify thoracic deflection in the purely lateral direction, limiting the ability for the ATD to accurately depict the nature of the human thorax under any loading that is not primarily lateral. To improve on NHTSA standards of protection, a better understanding of the human response to oblique, blunt loading is necessary for improving the biofidelity of ATD’s.

1.2 – Motivation

The motivation behind this study is to clarify differences seen in two related studies done in the Injury Biomechanics Research Lab previously. In 2006, Shaw et al observed the post-mortem human subject (PMHS) response to low energy impacts in both lateral and oblique directions.[3] Subjects were exposed to a single lateral impact as well as a single oblique impact, 30° anterior to lateral, on opposite sides at a velocity of 2.5 m/s at the 4th intercostal space, approximately mid-sternum (Figure 1).

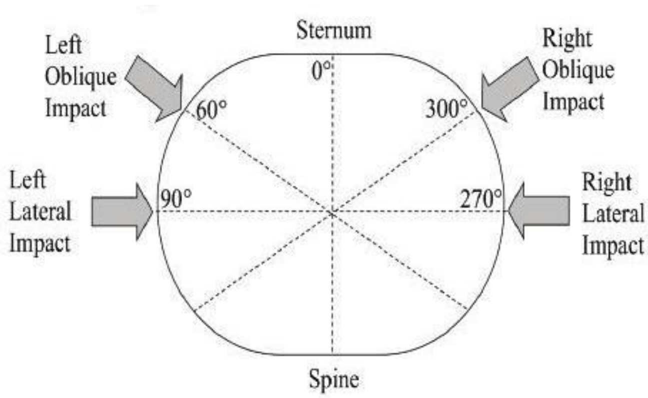

Figure 1: PMHS impact orientations for blunt trauma testing (Shaw et al., 2006)

Shaw's study concluded that lateral impacts sustained a greater force and incurred smaller deflections than the oblique impacts, creating distinctly different responses, as evidenced in Figure 2.

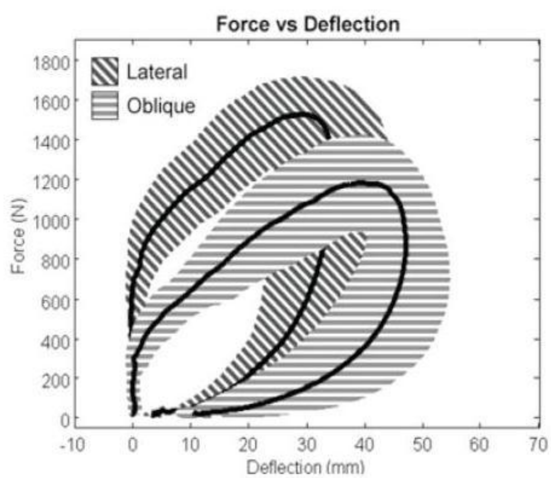

Figure 2: Force-deflection response targets published by Shaw et al. (2006)

In 2009, a study by Long used a similar protocol but impacted subjects at the level of the xiphoid process at speeds of 4.5 and 5.5 m/s, a more injurious energy level.[4] The results of his tests indicated similar responses in both lateral and oblique impacts. The testing also provided evidence of similar injury risk for impacts of equal energy levels in both the lateral and oblique directions.

Other than drawing different conclusions, the tests run by Shaw and Long also faced the challenge of calculating stiffness without gathering deflection values from the same point where the force was being applied and calculated. More details of the complications associated with this disparity will be discussed in the methods section as well as shown in the results section.

1.3 - Objectives

The biomechanical response of the thorax is the collective response of soft tissues such as muscle, fat, and connective tissue, hard tissues like the ribs and sternum, as well as the lungs and heart. When doing impact tests on this body region, especially when not impacting in the frontal plane, soft tissues can often be the first point of contact for the impactor, causing force and deflection to not coincide temporally or spatially. The purpose of this study was to determine the best method for calculating stiffness of the human thorax response to blunt loading in the lateral and oblique directions, regardless if force and deflection are measured at the same point. A consistent technique for calculating stiffness of this complex body region will allow for comparison of impact data across subjects and test series. The method determined to be most accurate and consistent will be used to analyze the data collected previously at the Injury Biomechanics Research Lab by Shaw and Long to determine the similarity or dissimilarity of oblique and lateral responses. The technique could also be used in other biomechanical applications where there is a disparity between deflection and force data collection points.

Chapter 2: Methods

This chapter will briefly explain the testing protocol used in collecting the thorax impact data, as well as going in depth into the processing of the data and stiffness calculation techniques being evaluated.

2.1 – Thorax Impact Protocol

All testing was conducted at the Injury Biomechanics Research Laboratory at The Ohio State University. A similar test set-up was used for the most recent tests done as was used by Shaw and Long. Tests were run at three different speeds, 2.5 m/s, 4.5 m/s, and 5.5 m/s. All three speeds and both impact directions are represented in the data being analyzed, see Table 1.

Table 1: Test speed and orientation matrix

Test ID	Impact Speed (m/s)	Impact Side	Orientation
0802LTH45L01	4.5	Left	Lateral
0803OTH45L01	4.5	Left	Oblique
0804OTH45L01	4.5	Left	Oblique
0901OTH45L01	4.5	Left	Oblique
0902LTH45L01	4.5	Left	Lateral
0903LTH45L01	4.5	Left	Lateral
0904LTH55L01	5.5	Left	Lateral
0906OTH45L01	4.5	Left	Oblique
1001LTH45L01	4.5	Left	Lateral
1002LTH45L01	4.5	Left	Lateral
1003OTH45L01	4.5	Left	Oblique
1101OTH25L01	2.5	Left	Oblique
1101LTH25R02	2.5	Right	Lateral
1101OTH45R03	4.5	Right	Oblique
1101LTH45L04	4.5	Left	Lateral
1201OTH25R01	2.5	Right	Oblique
1201LTH25L02	2.5	Left	Lateral
1201OTH45L03	4.5	Left	Oblique
1201LTH45R04	4.5	Right	Lateral

The protocol for the impact test is as follows. Before testing, cadavers are cleaned using a 10% bleach solution, anthropomorphic measurements are taken, and notes are made of any abnormalities. A computed tomography (CT) scan is administered to identify any previous rib fractures and to serve as a baseline. Mounts for a accelerometer and angular rate sensors are affixed to the sternum, T4, T8, and T12 spinous processes, allowing for motion analysis to be conducted on the spine.

Instrumentation of the ribs included a 40-channel chest band wrapped externally around the subject at the mid-sternum level and secured with tape. Strain gages were applied directly to the ribs and utilized to analyze time of fracture. Any incisions at the impact sites were closed with sutures. The subject was held initially with arms crossed at a position parallel with the floor and a head harness on a magnetic release holding the subject upright. The subject was released immediately prior to impact. (Figure 3)

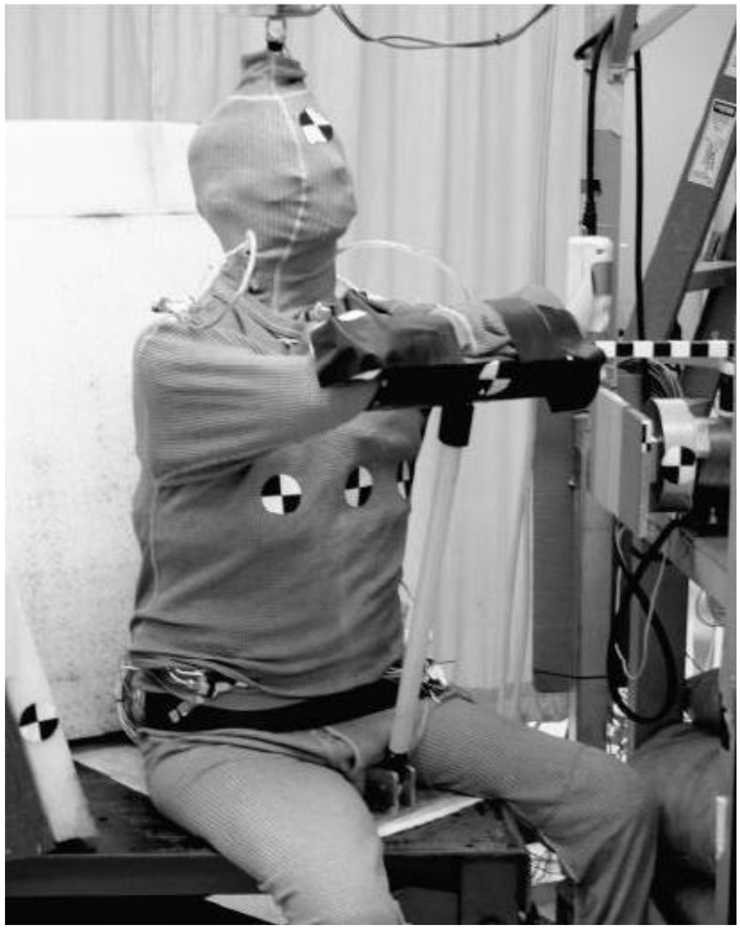

Figure 3: Test-set up for oblique impact test

A 96-channel data acquisition system was used to record data from the instrumentation. Signals were collected at a rate of 20 kHz. Deflection values were calculated from change in distance between sensors on the chest band. Force data was collected using a load cell on the impact ram. Since the load cell was not the direct point of impact, an accelerometer was also affixed to the ram so that the force data could be compensated for inertia.

A 23 kg pneumatic ram fitted with a 6”x12” steel plate as the surface of contact, was used to load the subject and reached near constant velocity prior to impact. An accelerometer monitored and recorded the ram’s velocity. Post-impact, subjects underwent a CT scan to monitor fractures that occurred during testing. A thoracic autopsy was conducted looking for injury to subcutaneous tissue, ribs, thoracic organs, as well as viscera and great vessels. A sample autopsy report can be seen in Appendix A.

2.2 – Data Processing

The raw data was zeroed, processed, and inertially compensated before being ready to be analyzed to determine stiffness. MATLAB (MathWorks Inc., Novi, MI) was utilized to do all of the data processing and analysis. Sample code from MATLAB can be found in Appendix B.

Zeroing the data compensates for any natural background signal that is present in the instrumentation, whether it is from the instrumentation itself, or the connections with the data acquisition system. To zero the data, the value of the initial data point was subtracted from the subsequent points, sufficiently compensating for the natural signal.

Filtering was the next step in processing. A 300 Hz low pass Butterworth filter was applied to the data using the filtfilt function in MATLAB. The filtfilt function filters the data both in the forward and reverse direction. The benefit of using this function is that there is no phase distortion of the data.

The last step in processing was to compensate the force data for the inertial effects of the impacting plate. To inertially compensate means to take into account the additional force that is experienced by the load cell, before impact, because of the impacting plate and other components. A simple mass multiplied by acceleration calculation was used to determine the value used to adjust the data for inertia. The weight used was 1.872 kg, which included the impacting plate, the four screws used to attach it to the load cell, and half of the load cell itself. To get the mass, the weight was multiplied by 9.83 m/s^2, the acceleration due to gravity. The mass was then multiplied by the acceleration of the ram which was gotten from the accelerometer on the ram itself. This resulting force value was calculated for every data point and subtracted from the raw data to create the finalized processed data which was used for stiffness calculation.

2.3 – Stiffness Calculation Methods

Stiffness was calculated for each of the 19 tests using seven different techniques. Stiffness, k, is defined as the force (F) per unit of deflection (δ) which in this study was mm, with force being measured in Newtons. (Equation 1)

$$k = F/\delta \qquad [1]$$

To visualize this relationship, force-deflection curves were created for each test; two such curves are shown in Figure 4.

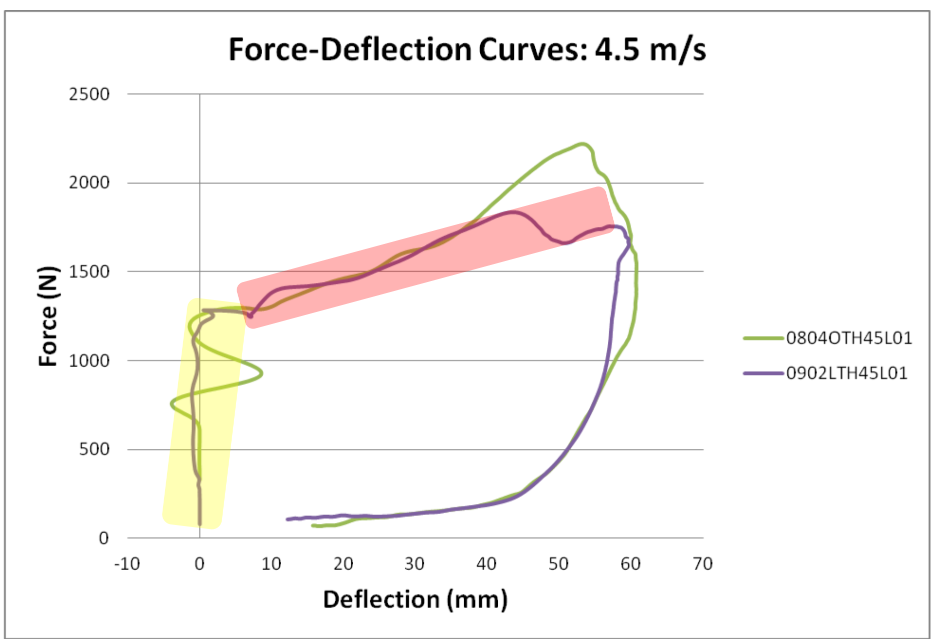

Figure 4: Sample Force-Deflection curves with loading (yellow) and deflection (red) regions labeled

Two of the key features to note in each force-deflection curve are the loading region and deflection region that are evident. In the loading region, the ram is experiencing a force before there is any deflection noticed by the chest band on the subject. This is likely due to the ram interacting with other parts of the anatomy, such as underarm fat tissue, before causing deflection at the level of the chest band. Because stiffness can only be calculated when deflection is present, different sections of the force-deflection curve were analyzed to see what would result in the most consistent and accurate stiffness values.

The first method used was selecting the instant of impact, time = 0 sec, as the initial point for calculation, and the force and deflection at the time of maximum deflection as the ending point. This was used under the assumption that this method may results in an average representation of the stiffness of the thorax over the full period of deflection. The second method also used the instant of impact as the initial point, but instead of ending at maximum deflection, it ended at the point of maximum force. This was analyzed so that the stiffness was only calculated while the ram was actively loading the subject, before it began to decrease loading.

The next set of methods used attempted to take into account only portions of the initial loading region, assuming that no deflection was seen until it was seen by the chest band. The first two techniques within this set sectioned out portions of the force-deflection curve based on percentages of the maximum force, 10-90% and 20-80%. The second two techniques focus instead on sectioning out based on percentages of the maximum deflection, again 10-90% and 20-80%.

The last method analyzed was a technique used by Margulies et al. in their 2000 study investigating suture properties in the infant skull.[5] The Margulies method finds the stiffness between every data point, keeping a running tally of average stiffness and standard deviation. As long as the calculated stiffness between two consecutive points on the force-deflection curve remains between the running average stiffness plus or minus one standard deviation, the sequence continues. As soon as one stiffness value falls out of the corridor, the average stiffness of all of the previous calculations is used as the stiffness value.

2.4 – Method Analysis

Once stiffness values were calculated using all seven of the techniques, averages and standard deviations were found for oblique and lateral tests and for low (2.5 m/s) and high (4.5 m/s) speeds. Plots of the sections of the force-deflection curves used for calculating stiffness were also created to give a visual representation of the stiffness section. To assess whether or not the Margulies method is working the way it is intended, plots were made to see when the stiffness values, deviated from the corridor.

Chapter 3: Results

This section includes the results of the stiffness calculation techniques. Summarized in Table 2 are the average calculated stiffness's for the high speed tests, 4.5-5.5 m/s, for both the oblique and lateral impacts.

Table 2: High speed test stiffness value analysis

High Speed Tests	Oblique	Lateral	Ob - Stdev	%	Lat - Stdev	%
Time = 0 to Max deflection	67.90	53.75	26.90	40%	31.21	58%
Time = 0 to Max force	36.98	33.92	12.87	35%	20.39	60%
10-90% Force	-1653.40	130.02	4774.97	-289%	102.60	79%
20-80% Force	29.86	33.12	4.88	16%	27.69	84%
10-90% Deflection	12.05	20.08	9.42	78%	20.34	101%
20-80% Deflection	9.92	18.17	8.57	86%	19.16	105%
Margulies Stdev method	7037.64	-5.28	18198.84	259%	42.99	-814%

A wide range of stiffness values were obtained depending on the method used with the highest values being seen using the Margulies method for oblique tests (7037.64 N/mm), and the 10-90% force method for lateral tests (130.02 N/mm). The lowest values were seen with the 10-90% force method for the oblique tests (-1635.40 N/mm), and the Margulies method for the lateral tests (-5.28 N/mm). The most consistent methods were the 20-80% force method for oblique tests (29.86 +/- 4.88 N/mm), and the instant of impact to max deflection for lateral tests (53.75 +/- 31.21 N/mm).

Table 3 summarizes the results from the stiffness assessments for the low speed tests, 2.5 m/s, for both oblique and lateral tests.

Table 3: Low speed test stiffness analysis

Low Speed Tests	Oblique	Lateral	O- Stdev	%	L- Stdev	%
Time = 0 to Max deflection	68.75	96.64	6.36	9%	57.05	59%
Time = 0 to Max force	35.08	65.69	5.24	15%	12.79	19%
10-90% Force	93.78	140.83	40.89	44%	92.34	66%
20-80% Force	30.30	46.03	0.82	3%	12.58	27%
10-90% Deflection	25.12	32.40	6.05	24%	5.11	16%
20-80% Deflection	25.55	33.29	4.03	16%	4.29	13%
Margulies Stdev method	0.50	-226.27	393.16	79357%	182.05	-80%

The low speed tests resulted in a smaller tighter range of values than the high speed tests. The highest values were calculated using the 10-90% maximum force for both the oblique tests (93.78 N/mm) and the lateral tests (140.83 N/mm). The lowest values resulted from the Margulies method for the oblique tests (0.50 N/mm) and for the lateral tests (-226.27 N/mm). The most consistent methods were the 20-80% force method for oblique tests (30.30 +/- 0.82 N/mm), and the 20-80% maximum deflection method for lateral tests (33.29 +/- 4.29 N/mm).

The stiffness values calculated for each individual test can be found in Appendix C. Figures 5-16 display the sectioned portions of the force-deflection plots that were used to calculate the individual stiffness values:

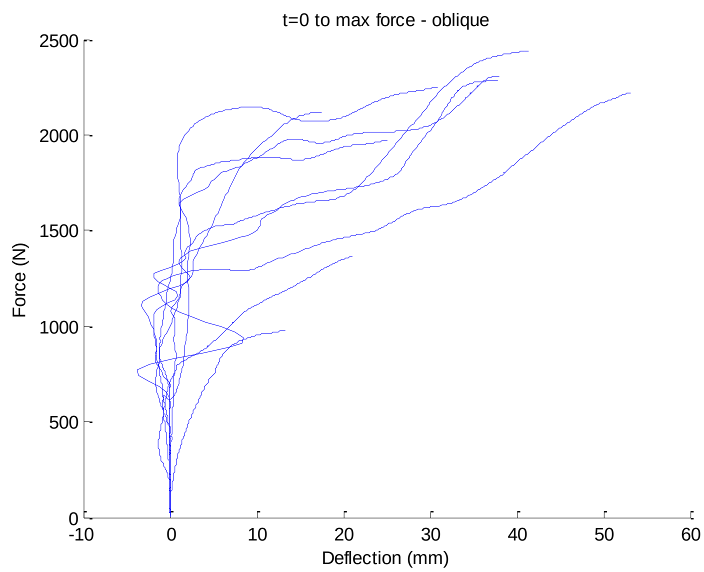

Figure 5: Time of impact to maximum force section – oblique

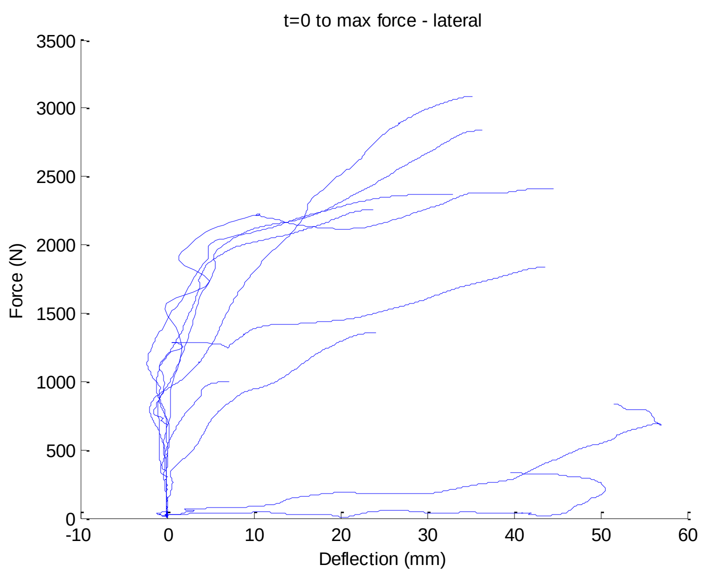

Figure 6: Time of impact to maximum force section – lateral

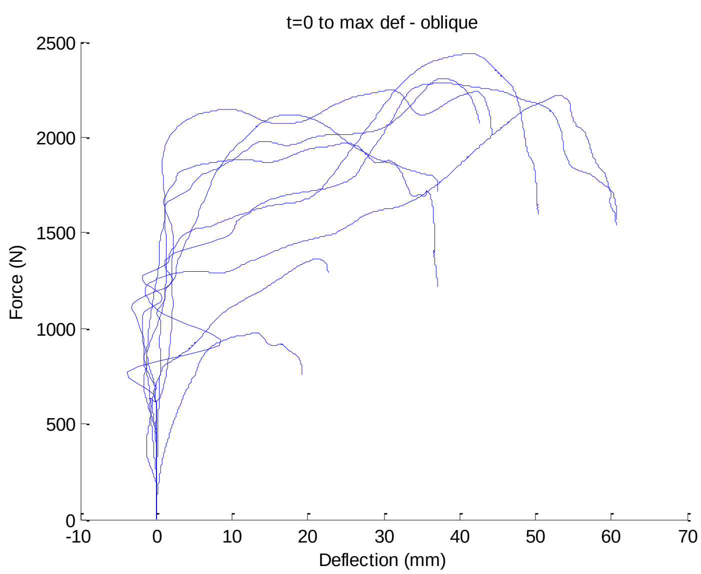

Figure 7: Time of impact to maximum deflection section – oblique

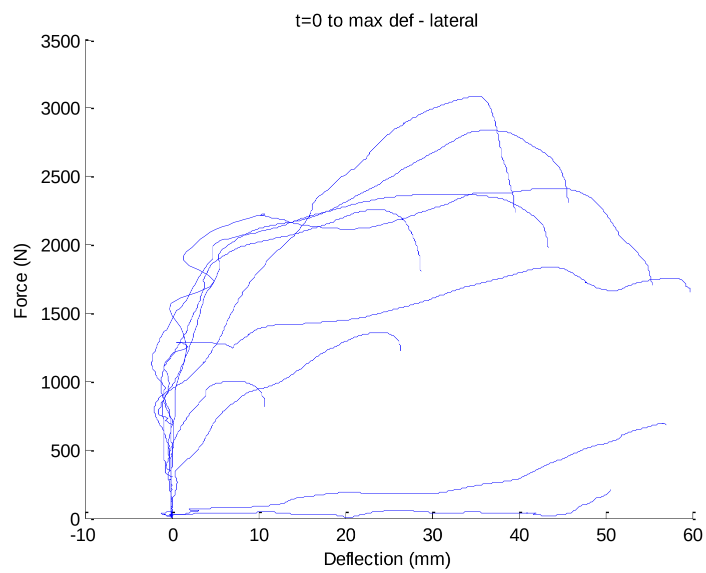

Figure 8: Time of impact to maximum deflection section – lateral

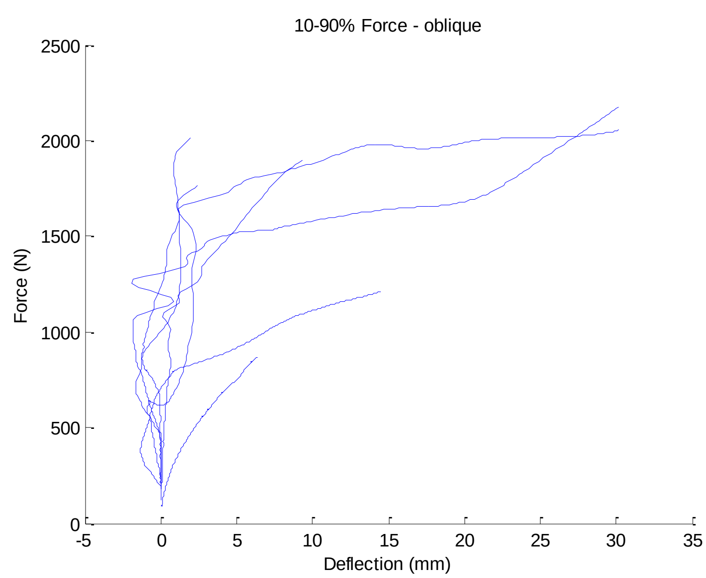

Figure 9: 10-90% Maximum force section – oblique

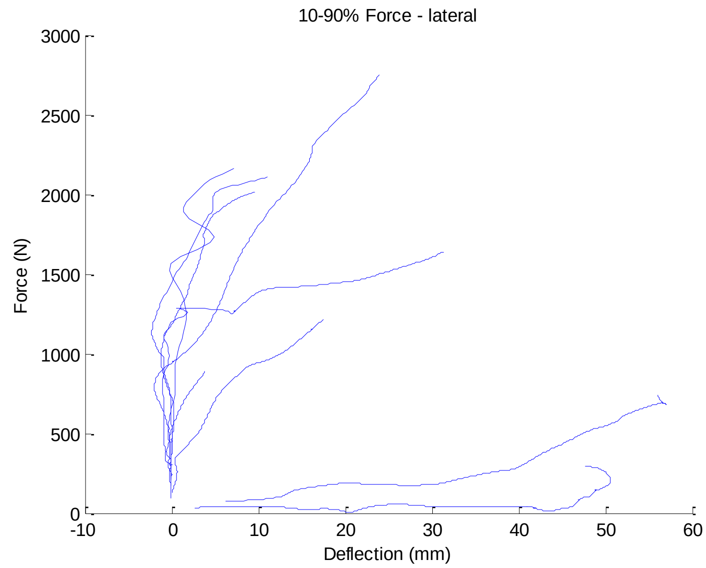

Figure 10: 10-90% Maximum force section – lateral

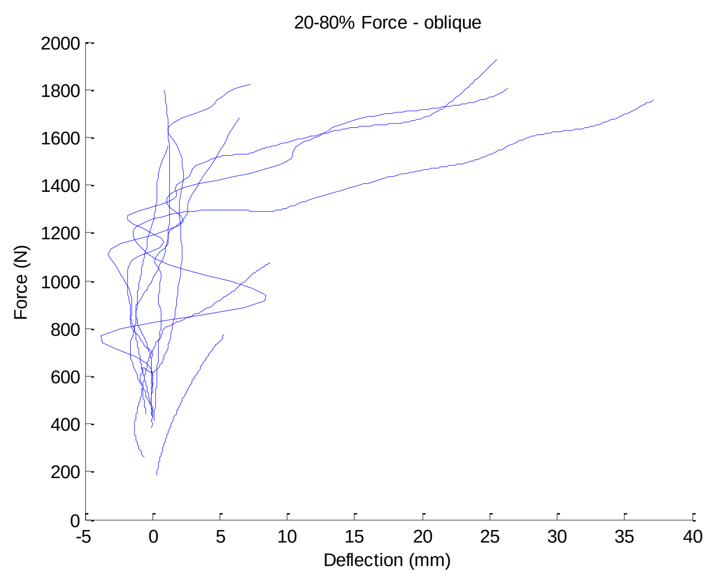

Figure 11: 20-80% Maximum force – oblique

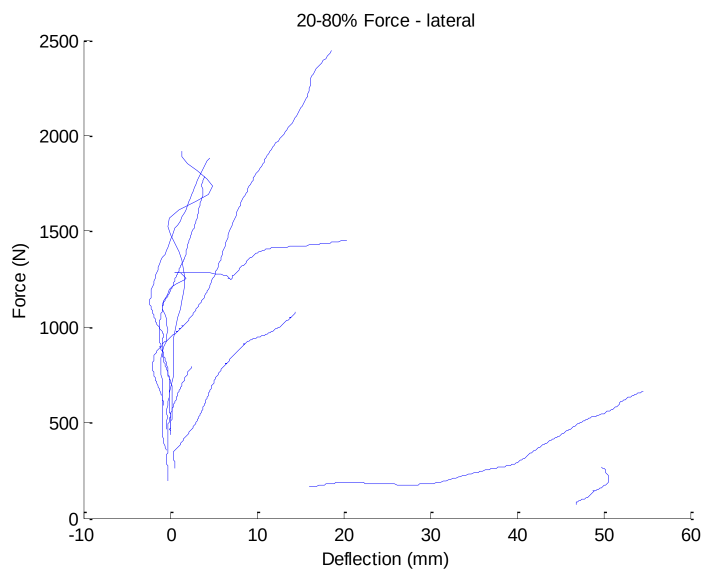

Figure 12: 20-80% Maximum force section – lateral

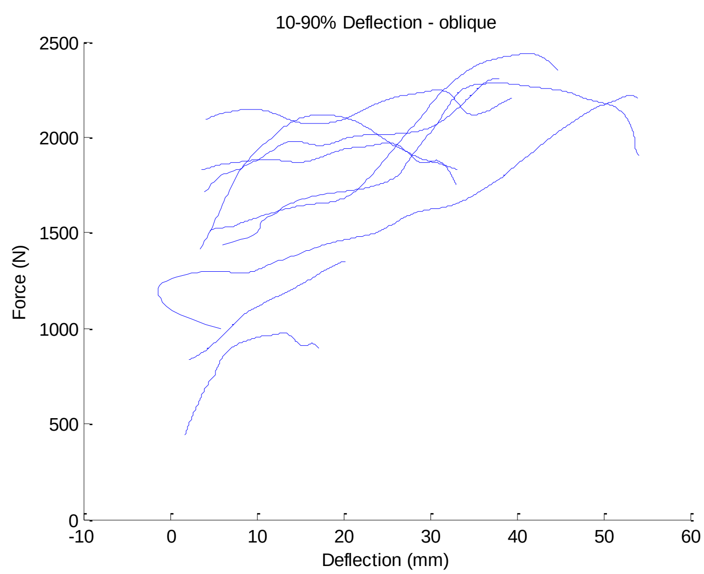

Figure 13: 10-90% Maximum deflection section – oblique

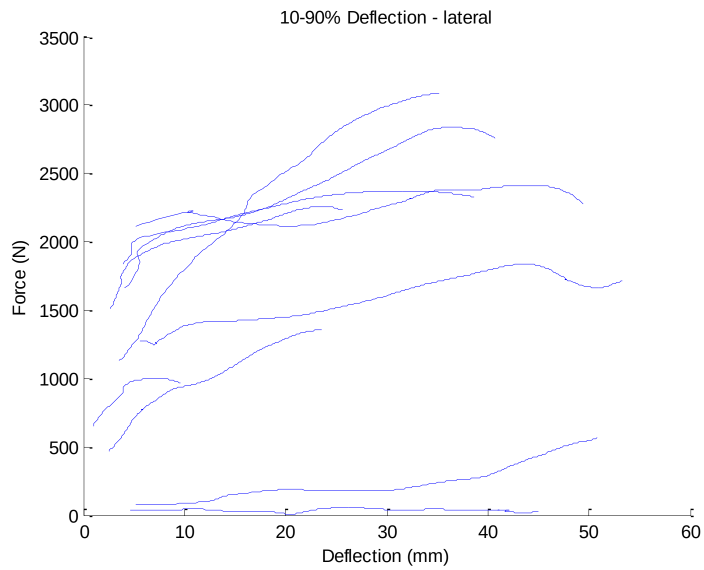

Figure 14: 10-90% Maximum deflection section – lateral

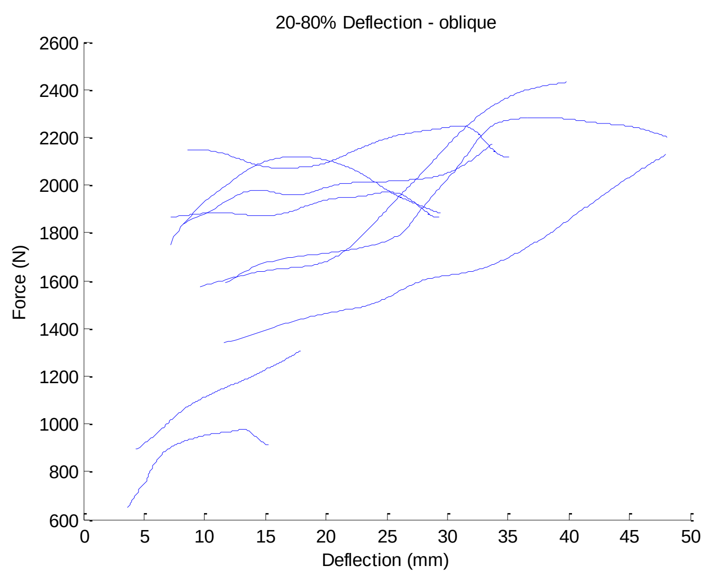

Figure 15: 20-80% Maximum deflection section – oblique

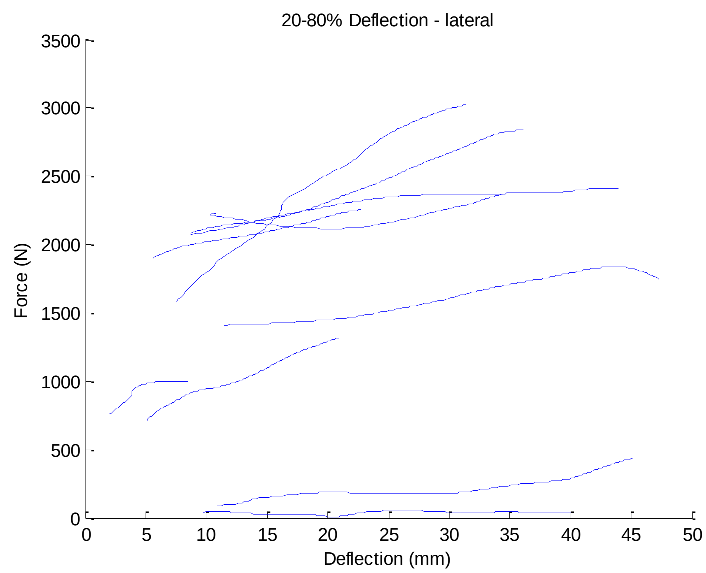

Figure 16: 20-80% Maximum deflection section – lateral

The sectioned portions of the force-deflection curves show that when looking at percentages of maximum force (Figures 9-12), the main section that is utilized for stiffness calculations is the loading portion, which does not account for much of the deflection. Figures 13-16 resemble the deflection portion of the force-deflection curve, not incorporating much of the force change that initiates the deflection.

Chapter 4: Discussion

4.1 – Discussion

The purpose of this study was to determine the most accurate and consistent method for determining the biomechanical stiffness of the human thorax when the point of measurement of force and deflection do not coincide. From the data collected, a weighted percentage was created to highlight the method that had the lowest standard deviation across testing speeds and orientations. Table 4 presents the results of this analysis.

Table 4: Percentage standard deviation by stiffness calculation method

Weighted Percentage Stdev by Method	
Time = 0 to Max deflection	46%
Time = 0 to Max force	41%
10-90% Force	-71%
20-80% Force	43%
10-90% Deflection	75%
20-80% Deflection	79%
Margulies Stdev method	8126%

According to the results in Table 4, the most consistent method to use would be using the initial time of impact to the time of the maximum applied force to calculate stiffness. This also makes sense with a visual check by observing the nature of the sectioned portions for this calculation method plotted in Figures 6 and 7. The sections used incorporate both the loading and deflection portions of the curves, not leaving out important data as to what the body is experiencing.

Another interesting trend to appear in the data is that at high speed tests, the impact time to maximum force yields relatively similar stiffness values in oblique and lateral tests, 36.99 N/mm and 33.92 N/mm respectively. (Table 2) At low speeds, using the designated stiffness calculation technique, very different stiffness values result for oblique and lateral impacts, 35.08 N/mm and 65.69 N/mm respectively. (Table 3) This supports the conclusions that both Long and Shaw made in their individual studies.

To improve this study, more subjects and data points would allow for a higher level of significance and clearer range of data. Also, improvements in the technique of the Margulies method would allow it to be used for scenarios such as high speed impact testing where there is a high amount of variation in the data.

Going forward, these methods could be continually used and assessed as too which technique is better for certain applications. Carrying out the same analysis on a different type of biomechanical testing to try and confirm the results would increase the strength of this study as well.

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Appendix A: Sample Autopsy Report

Autopsy Date: 4/21/2011

Autopsy Report

1101

- Diaphragm:
  - No Injury
- Heart & Aortic Arch:
  - No Injury
- Kidney:
  - No Injury
- Liver:
  - Gall bladder previously removed
- Lung:
  - No Injury
- Pancreas:
  - No Injury
- Pericardium:
  - No Injury
- Pleura:
  - No Injury
- Pulmonary Artery:
  - No Injury
- Rib Cage:
  - No Injury
- Spleen:
  - No Injury

Other Notes:

- Tissue thickness at impact site: (cm)

	Left Oblique	**Right Oblique**	**Right Lateral**	**Left Lateral**
Upper ram edge	0.6	0.8	0.7	1.0
Middle of ram	1.5	1.5	1.4	0.8
Lower ram edge	0.6	1.2	1.3	0.8

- Strain Gage Notes
    - Left Side
        - N/A
    - Right Side
        - R4 Lat – bottom of strain gage lifted off of bone
        - R6 Lat – glue coming off but gage is still secure

AIS Code Summary – Not applicable because no injuries were documented during autopsy.

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Appendix B: Sample MATLAB Code

B.1- Data Processing Code

```
%% Thorax Force Processing
% Upload and process IBRL thorax impact force data. Zero, Filter,
% Compensate
clear all
clc

% Prompt user to pick file to process
[datafile, path] = uigetfile('*.csv','Choose Data File');

%% Load in Data
% time - time column
% data - 1: Event (V)
%        2: RamXG (G)
%        3: RamFZ (N)
%        4: RamFY (N)
%        5: RamFx (N)
% Some files may have different data columns, so check before
continuning
% to make sure the columns correspond to the right data
cd(path);

[num, text, raw] = xlsread(datafile,'A1:F16');
time = xlsread(datafile,'A17:A60016');
data = xlsread(datafile,'B17:F60016');

%% Zero Data
% data_z corresponds to zeroed data
for i=1:5
     data_z(:,i)=data(:,i)-data(1,i);
end

%% Filter Data
% Butterworth 300 Hz low pass
for t=1:5
    freq = 1./median(diff(time(:,1)));
    Nyquist = freq./2;
    % Define filter frequency by modifying numerator of Wn calculation
    Wn = 300./(Nyquist);
    [B,A] = butter(2,Wn,'low');
    data_z_filt(:,t) = filtfilt(B,A,data_z(:,t));
end

%% Compensate for Intertia
% Subtract inertial effect on force (Accel*Mass of 1/2 load cell, plate
and
% four screws)
```

```
for t=3:5
    if max(data_z_filt(:,t))>=800
        data_z_filt_comp(:,t) = data_z_filt(:,t)-
data_z_filt(:,2)*(1.872*9.83);
    else
        data_z_filt_comp(:,t) = data_z_filt(:,t);
    end
end

data_z_filt_comp(:,1:2)=data_z_filt(:,1:2);
```

B.2 – Margulies Method

```
%% Stiffness Calculation Marguiles Method
% 2403 is time = 0
% Oblique
for t = 1:obtests
    figure
    hold on
    for i = 2403:length(oblique(:,1,t))
        obs_m(i-2402,t) = (oblique(i,3,t)-
oblique(2402,3,t))/(oblique(i,2,t)-oblique(2402,2,t));
    end
    for i = 1:length(obs_m(:,t))
        avg_ob(i,t) = mean(obs_m(1:i,t));
        stdev_ob(i,t) = std(obs_m(1:i,t));
        stiffcheckup(i,t) = avg_ob(i,t)+stdev_ob(i,t);
        stiffchecklow(i,t) = avg_ob(i,t)-stdev_ob(i,t);
    end
    % # of Points outside range
    counter = 1;
    for i = 1:length(obs_m(:,t))
        low = obs_m(i,t) >= stiffchecklow(i,t);
        up = obs_m(i,t) <= stiffcheckup(i,t);
        check = up + low;
        if check == 2
            if counter <= 5
                obstiff(7,t) = mean(obs_m(1:i,t));
            else
            end
        else
            counter = counter + 1;
        end
    end

    %plot(1:length(obs_m(1:i,t)),obs_m(1:i,t),'k')
    %plot(1:length(stiffcheckup(:,t)),stiffcheckup(:,t),'-r')
    %plot(1:length(stiffchecklow(:,t)),stiffchecklow(:,t),'-b')
    title('Margulies Check - Oblique')
    ylabel('Stiffness (N/mm)')
```

```
end
```

Appendix C: Stiffness Calculation Results

Impact Angle	L	O	O	O	L
Speed	High	High	High	High	High
Test ID	0802LTH45L01	0803OTH45L01	0804OTH45L01	0901OTH45L01	0902LTH45L01
Time = 0 to Max deflection	53.91	51.35	35.55	76.80	40.24
Time = 0 to Max force	30.47	20.19	19.87	31.70	26.38
10-90% Force	265.55	-1053.04	-12390.68	645.93	46.76
20-80% Force	26.52	23.71	22.06	32.03	18.73
10-90% Deflection	3.84	9.82	25.11	-2.69	9.14
20-80% Deflection	5.71	16.81	21.68	-0.06	9.48
Margulies Stdev method	27.72	-359.32	102.51	48267.27	6.91

Impact Angle	L	L	O	L	L	O	O
Speed	High	High	High	High	High	High	Low
Test ID	0903LTH45L01	0904LTH55L01	0906OTH45L01	1001LTH45L01	1002LTH45L01	1003OTH45L01	1201OTH25R01
Time = 0 to Max deflection	8.23	15.76	60.32	59.09	70.73	58.54	64.25
Time = 0 to Max force	3.91	11.49	48.16	35.59	44.68	48.16	31.37
10-90% Force	5.92	13.43	61.04	246.85	171.10	61.04	64.86
20-80% Force	-9.86	18.02	32.90	84.66	32.93	32.90	29.73
10-90% Deflection	-0.30	10.76	17.44	29.84	13.91	17.44	20.84
20-80% Deflection	-0.01	10.16	13.08	27.44	11.38	13.08	28.40
Margulies Stdev method	-31.60	-32.51	-381.26	3.45	49.03	-381.26	-277.51

Impact Angle	L	O	L	O	L	O	L
Speed	Low	High	High	Low	Low	High	High
Test ID	1201LTH25L02	1201OTH45L03	1201LTH45R04	1101OTH25L01	1101LTH25R02	1101OTH45R03	1101LTH45L04
Time = 0 to Max deflection	56.30	72.16	87.37	73.25	136.98	120.62	94.66
Time = 0 to Max force	56.65	45.16	56.36	38.79	74.73	45.69	62.50
10-90% Force	75.53	917.76	102.87	122.70	206.12	184.11	187.69
20-80% Force	37.14	31.18	46.58	30.88	54.93	34.28	47.41
10-90% Deflection	28.79	3.23	61.85	29.39	36.01	14.05	31.61
20-80% Deflection	30.26	-1.00	60.68	22.70	36.33	5.89	20.57
Margulies Stdev method	-97.55	1928.42	-86.24	278.50	-355.00	87.13	20.96